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Hemodynamics of small aneurysm pairs at the internal carotid artery

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ABSTRACT

Cerebral aneurysms carry significant risks because rupture-related subarachnoid hemorrhage leads to serious and often fatal consequences. The rupture risk increases considerably for multiple aneurysms. Multiple aneurysms can grow from the same location of an artery, and the interaction between these aneurysms raises the rupture risk even higher. Four aneurysm pair cases at the internal carotid artery are investigated for their hemodynamic behaviors using patient-specific modeling. For each case, aneurysms are separated from the parent artery and three models are reconstructed, one with two aneurysms and the other two models with only one of the two aneurysms. Results show that the relative anatomic location of one aneurysm to the other may determine the hemodynamic environment of an aneurysm. The presence of a proximal aneurysm reduces the intra-aneurysmal flow into the distal aneurysm; the proximal aneurysm and larger aneurysm have a greater area under low wall shear stress. The average intra-aneurysmal inflow ratio ranges from 16% to 41%, and reduction of the inflow ratio by an aneurysm pair varies from 6% to 15%. The maximum wall shear stress increases for serial aneurysms, but decreases for parallel aneurysms. Interaction between parallel aneurysms is not significant; however, the proximal aneurysm in serial aneurysms may be subject to a greater rupture risk.

1. Introduction

Enlargement of a cerebral artery leads to formation of an intracranial aneurysm, and harboring an intracranial aneurysm carries a significant rupture risk. The 5-year cumulative rupture rate for aneurysm size between 7 and 12 mm is 2.6% for aneurysms at the anterior circulation and 14.5% for aneurysms involving the posterior circulation [1]. The rupture rate rises to 40–50% for giant aneurysms; even the rupture risk of small aneurysms cannot be ignored, especially for multiple aneurysms [2]. One study showed that 12% of aneurysms treated by coil embolization were small ruptured aneurysms (<3 mm) [3]. Despite the improvement of aneurysm treatment, more than 25% of patients either died or were disable at 1 year after treatment for aneurysmal subarachnoid hemorrhage [4].

Approximately 20–30% of aneurysm patients have multiple aneurysms [5–7]. Multiple aneurysms not only challenge aneurysm management [8,9], but also render unfavorable prognosis for older patients [6]. Multiple aneurysms in the anterior circulation appear 66% unilaterally and 20% bilaterally [10], and it is very common to have multiple aneurysms at one internal carotid artery.

Patients with intracranial aneurysms tend to be hypertensive (20%) and are more like to smoke (42%), and majority of aneurysm patients are female (67%). People with these risk factors are also susceptible to multiple aneurysm [5,7,11]; 40% of patients with multiple aneurysms are hypertensive, 82% of them smoking, and 90% of them are female. Aneurysm multiplicity can have a greater impact on rupture risk than does aneurysm location [12]. Annual rupture rate is 1.9% for a single aneurysm, but 6.8% for multiple aneurysms.

Because of the critical role of hemodynamics in formation and rupture of intracranial aneurysms [13] and an increase in rupture risk for multiple aneurysms, we hypothesize that adjacent aneurysms may influence each other in hemodynamics. This may affect their rupture and/or growth rate. For this purpose, we analyze four patients with multiple intracranial aneurysms (<10 mm), and each patient has two aneurysms at the supraclinoid segment of his/her internal carotid artery. These aneurysms are referred to as aneurysm pairs, for which two aneurysms grow from the same site of an artery [14,15]. In each case aneurysms are studied individually and together using patient-specific hemodynamic modeling. Results of this analysis may shed light on the hemodynamic interaction of two aneurysms, and findings may provide important information on management of these multiple aneurysms.

2. Methods

Four patients with two intracranial aneurysms at the supraclinoid segment of the internal carotid artery (ICA) were selected for

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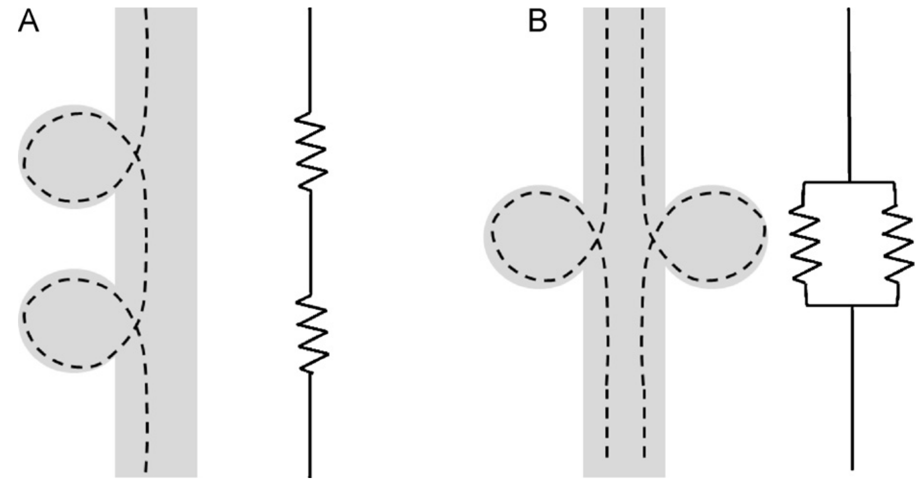

Fig. 1. Classification of aneurysm pairs and their electric analogies. Dashed lines are for the streamlines. (A) A serial aneurysm pair and (B) a parallel aneurysm pair.

this study. These aneurysms ranged from 3 to 9 mm in size. The two aneurysms in the first two patients (A and B) were on the same side of the ICA and almost touching each other (henceforth referred to as serial aneurysms). The two aneurysms for the other two patients (C and D) were on the opposite side of the ICA (henceforth referred to as parallel aneurysms). The definitions of serial and parallel aneurysms are based on blood flow pattern; their electric circuit analogies are presented in Fig. 1. It is possible for a blood cell to travel through both serial aneurysms, but it is highly unlikely for the same blood cell to enter both aneurysms in a parallel aneurysm pair.

Aneurysm models were reconstructed from the 3D digital subtraction angiographic (DSA) images obtained from Siemens AXIOM Arties dBA (Siemens Medical Solutions). The 3D DSA images were first segmented by Volview (Kitware). Each reconstructed model started from the petrous segment of the ICA and included the ICA bifurcation and portions of the anterior and middle cerebral arteries (ACA and MCA). A long section of the ICA ensured that the intra-aneurysmal flow would not be affected by the inflow boundary condition. The parent vessel was reconstructed independently based on its centerline and diameter along the vessel using Rapidform XOR (INUS Technology). The two aneurysms then were separated from the model. For each patient, three models were generated. The first model included both aneurysms, and the other two models had only one of two aneurysms.

In the following discussion, patients would be referred as A, B, C, and D; the aneurysms in each patient would be referred by numbers. For example, A1 and A2 are two aneurysms coexisting on patient A; A3 is essentially the same aneurysm as A1, but without A2. Similarly, A4 is the aneurysm without its neighboring aneurysm. These four cases are shown in Fig. 2 and each aneurysm is numbered in the figure. Because the viewing angle is different for each model, aneurysms may appear slightly different and this does not mean that aneurysm morphology has been altered. Table 1 lists the size for each aneurysm. The aneurysm size (largest aneurysm dimension) in Table 1 was measured on 3D DSA and used by our neuroradiologists for clinical diagnosis and decision for treatment. Coincidentally, there is one case in each group with comparable aneurysm size (B and C) and one case with different aneurysm sizes (A and D). Note that the ICA for case B (4.2 mm) was smaller than the other three cases (5.3–5.4 mm).

A commercial CFD package FLUENT (ANSYS) was used for flow analysis. An ICA waveform based on Ford et al. was used at the inlet for all cases [16]. The mean flow rate at the ICA was 4.5 ml/s, and peak flow rate 7.1 ml/s. The flow rate ratio between the ACA and MCA was based on their sizes so that the mean wall shear stresses at these branches were the same [17]. Each period consisted of 100 time steps and every calculation was repeated for 3 periods using an implicit second-order approach. At each time step, iteration continued until residues were reduced by 4 orders of magnitude. Grid-independence tests were conducted for each case to ensure that the difference in the wall shear stress was less than 3%. The final mesh size for these cases were 4.8×10^6 for patient A, 5.2×10^6 for patient B, 4.6×10^6 for patient C, and 8.5×10^6 for patient D.

For quantitative analysis of hemodynamic variables, high wall shear stress (WSS) and area of low WSS were studied. The threshold for low wall shear stress was 0.4 Pa [18]. The amount of intra-aneurysmal flow rate at the neck for each case was also computed.

3. Results

Analysis of flow pattern shows a single vortical structure within each of these aneurysms. There are no significant changes of streamlines due to the presence of a neighboring aneurysm so the effect of an aneurysm pair is not obvious in flow pattern. This might be a result of smaller aneurysm sizes and regular aneurysm shape.

Fig. 2 shows the distribution of average WSS for all aneurysms. The difference among the cases is hardly noticeable. In general, the WSS is higher at the distal neck, and the WSS at the aneurysm is lower than that in the parent artery.

The oscillatory shear index (OSI) is shown in Fig. 3. Elevated OSI can be observed only in very limited regions, and most areas have very low OSI. The difference in OSI is very small for patients B, C, and D, but the difference is greater for patient A. There is an

Table 1
Aneurysm size for each aneurysm and their relative location.

Case	ICA (mm)	Aneurysm	Size (mm)	Relative location
A	5.3	A1, A3	5.3	Distal
		A2, A4	8.5	Proximal
B	4.2	B1, B3	2.7	Distal
		B2, B4	2.9	Proximal
C	5.3	C1, C3	4.0	Distal, inferior
		C2, C4	5.0	Proximal, superior
D	5.4	D1, D3	4.2	Inferior
		D2, D4	7.0	Superior